

fsPHENIX: a physics outline and a to-do list towards a formal LOI

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What p+p and p+A@RHIC cannot do

(at least in the near future)

- Forward rapidity charged hadron production: π^\pm , K^\pm , ϕ (K^+K^-), p , Λ (πp), Ξ , $p\bar{p}$, anti- Λ etc. forward charged particle spin-correlations, forward jets, particle azimuthal distribution inside a forward jet...
STAR and PHENIX limited by the current magnets and forward detector design.
- Final state particle polarization at forward rapidity.
spin-transfer, induced polarization etc.
- High statistic Drell-Yan measurements.
 - a clean access to sea quarks' density, helicity and angular motion without the complication of quark to hadron fragmentation functions.

fsPHENIX wishlist (my own long version)

- Hadron production: $\pi^\pm, \pi^0, \eta, K^\pm, K_s, \phi, p, \Lambda, \Xi, p\bar{p}$, anti- Λ (and prompt photon)
 - $\pi^\pm, \pi^0, \eta, K^\pm, K_s$, proton single-spin asymmetries. Left-right bias originated from valence quarks.
 - $\phi, p\bar{p}$, anti- Λ single-spin asymmetries. Left-right bias originated from sea quarks, including strange quarks.
 - Spin transfer to Λ and Ξ : access quark transversity.
 - Forward two-hadron transverse spin-correlations: access quark transversity.
 - Forward jet
 - Particle azimuthal distribution inside a forward jet.
- Hadron production and spin asymmetries in $p+A$:
 - parton distributions in nuclei, EMC effects.
 - cold near matter effects.
 - Collins effect, transversely polarized quark fragment through a nuclei, use nuclei as a filter.

Wish list (cont.):

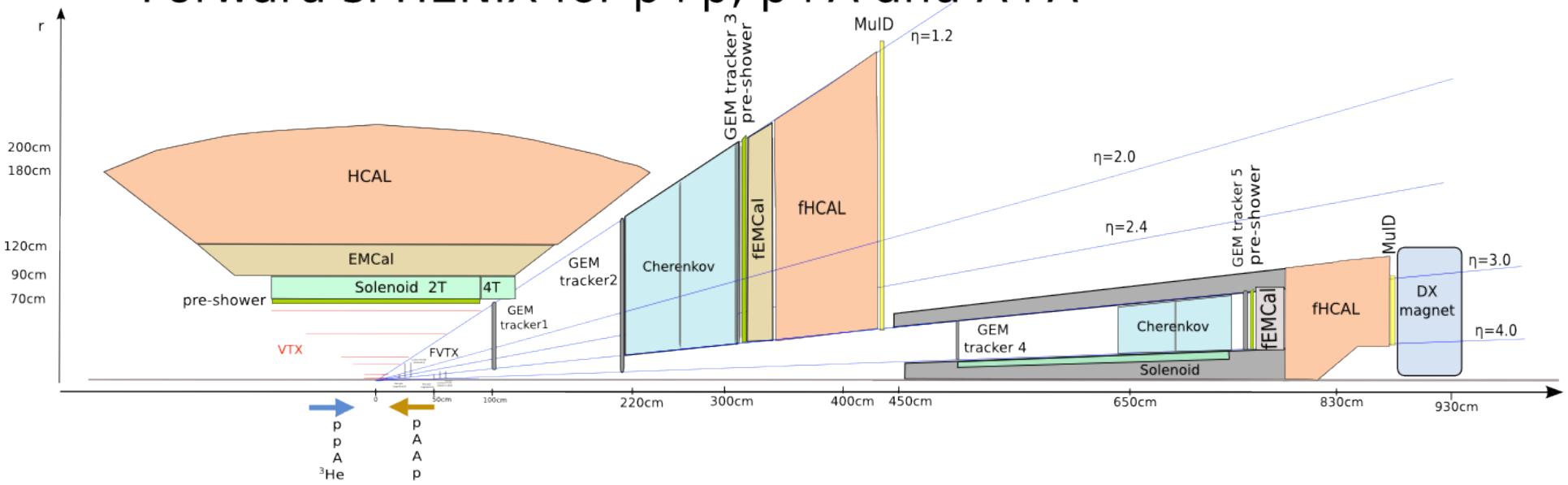
- Higher statistic Drell-Yan in p+p
 - to access sea quark information without the complication of fragmentation functions.
- Higher statistic Drell-Yan in p+A
 - Sea quark density asymmetry in nuclei.
 - Quark energy loss.
 - Quark transverse momentum broadening through nuclei.

fsPHENIX physics: a short list for LOI.

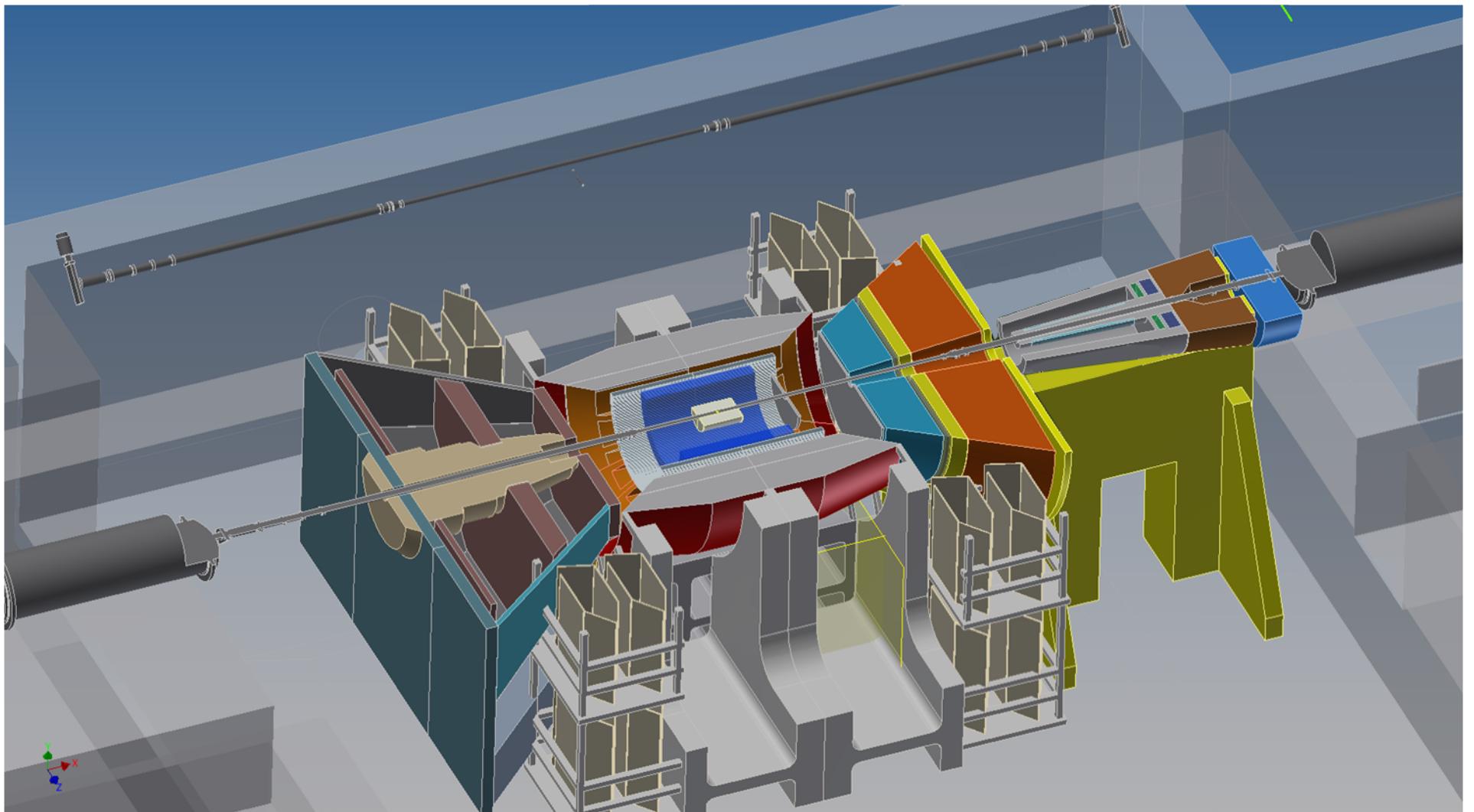
for fsPHENIX LOI, we will highlight the following measurements:

- Polarized Drell-Yan, single-spin and double-spin asymmetries.
- Forward jets, and hadron azimuthal distributions inside a jet.
- Prompt photon.
- Forward Lambda.

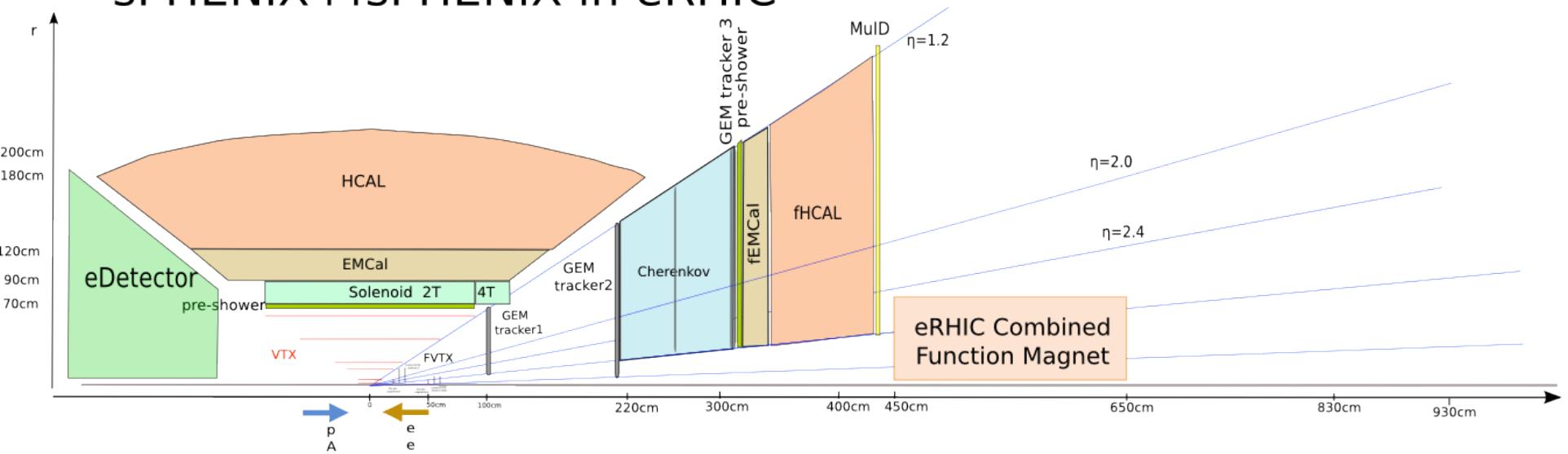
Forward sPHENIX for p+p, p+A and A+A



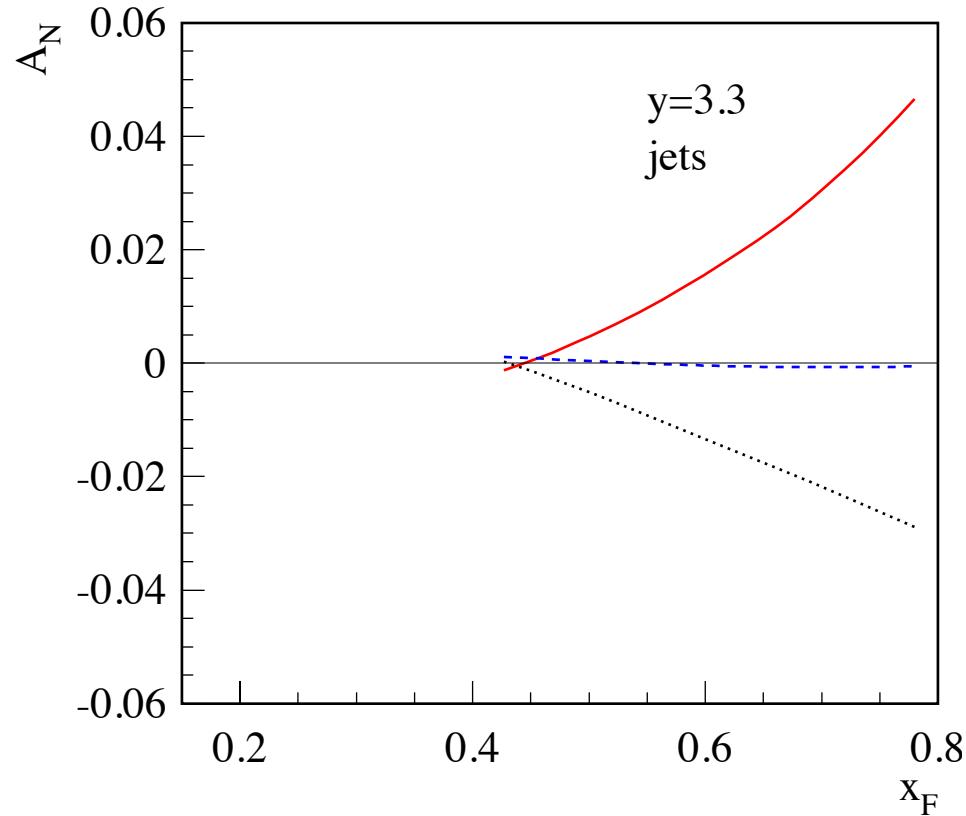
A cut-off view with South muTr in place



sPHENIX+fsPHENIX in eRHIC



200 GeV p+p Jet A_N



twist-3 approach “direct” extraction.

Fit of SIDIS data, new functional form.

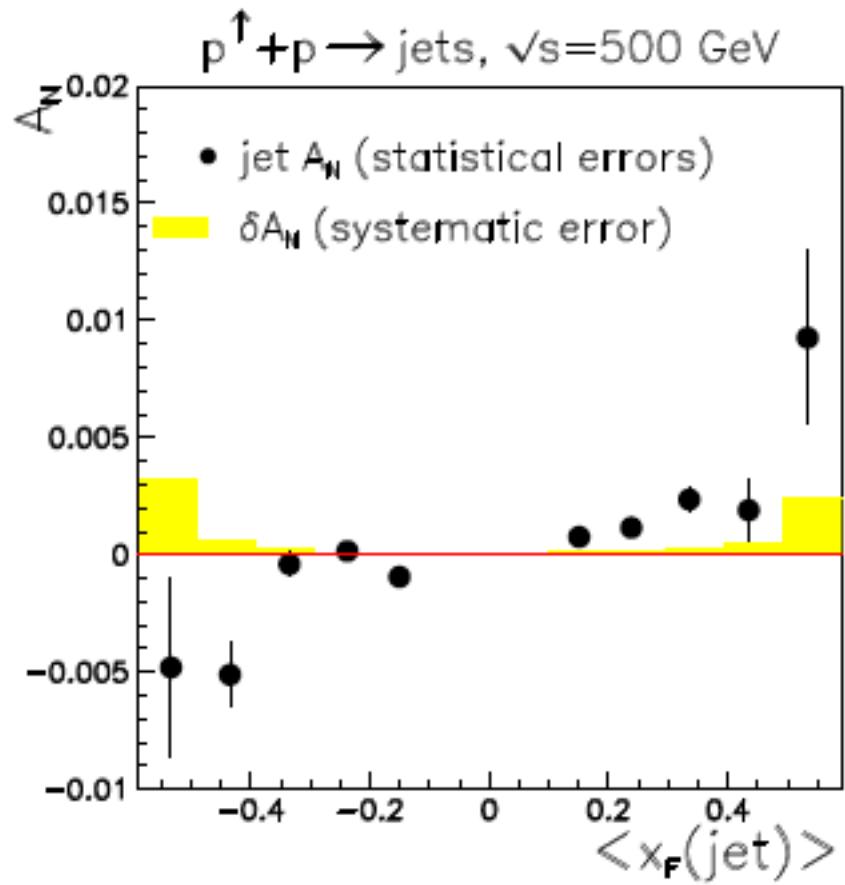
Fit of SIDIS data, old functional form.

Zhong-Bo Kang et al. arXiv:1103.1591

fsPHENIX can provide a clear answer to help resolving the puzzle on quark Sivers distributions.

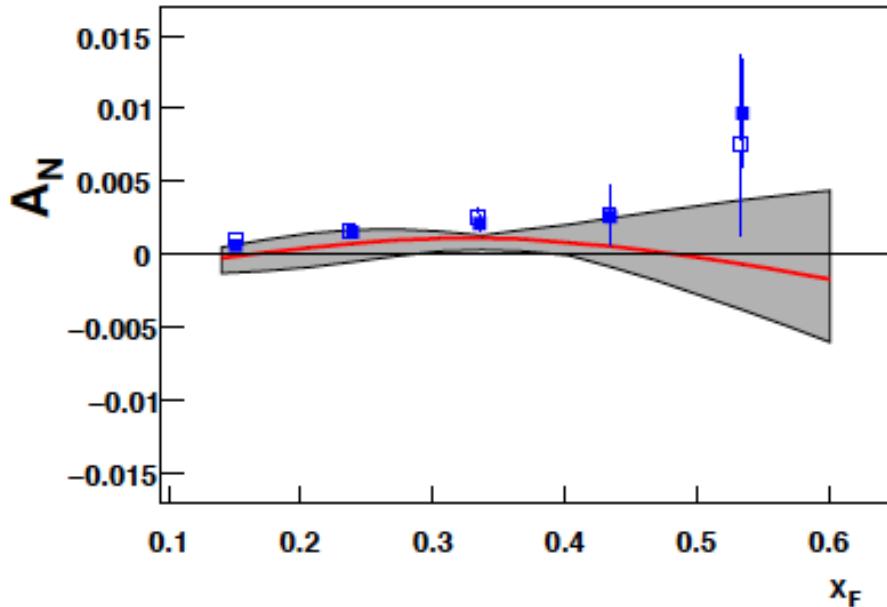
AnDY Jet A_N

arXiv:1304.0454



- Non-zero asymmetry in forward jet.
- A lot of room for improvements

FIG. 4: Analyzing power for forward jet production. Jets are reconstructed with the anti- k_T algorithm using $R_{jet} = 0.7$. Preliminary results [22] reported comparable A_N with the mid-point cone algorithm. Systematic error estimates are described in the text, and do not include scale uncertainty from the beam polarization measurements.



Gamberg, Kang and Prokudin
arXiv:1302.3218

FIG. 3. Description of AnDY preliminary data [16] for inclusive jet production at forward rapidity $\langle y \rangle = 3.25$ and center-of-mass energy $\sqrt{s}=500$ GeV. Shaded region corresponds to the parameter scan.

experimental data. Our result provides a first indication for the process-dependence of the Sivers effect and further demonstrates consistency between the TMD and collinear twist-3 factorization formalisms. However, due to the large uncertainty of the current preliminary data from AnDY and the small size of the jet spin asymmetry, our result cannot provide conclusive confirmation for process-dependence. Thus we also propose direct photon spin asymmetry along with DY measurements to test the process dependence of the Sivers effect. They are comple-

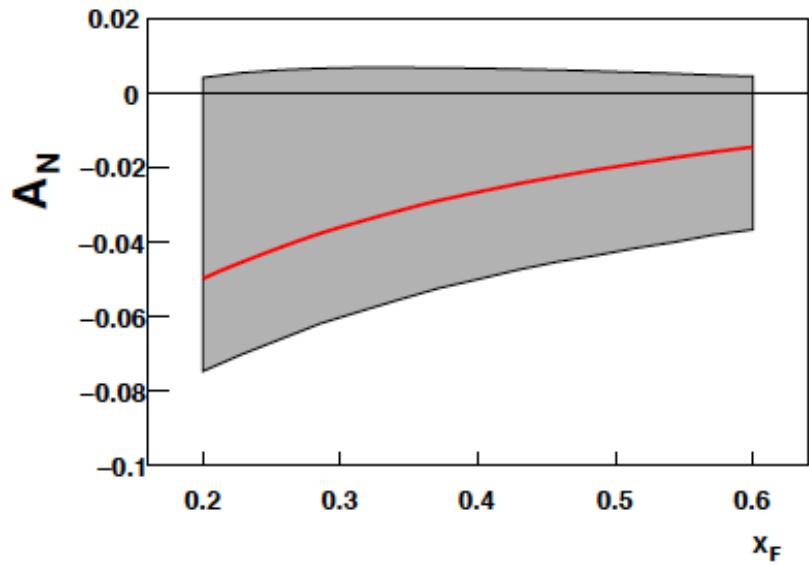


FIG. 4. Prediction of direct photon A_N in pp collisions at rapidity $y = 3.5$ and center-of-mass energy $\sqrt{s}=200$ GeV.

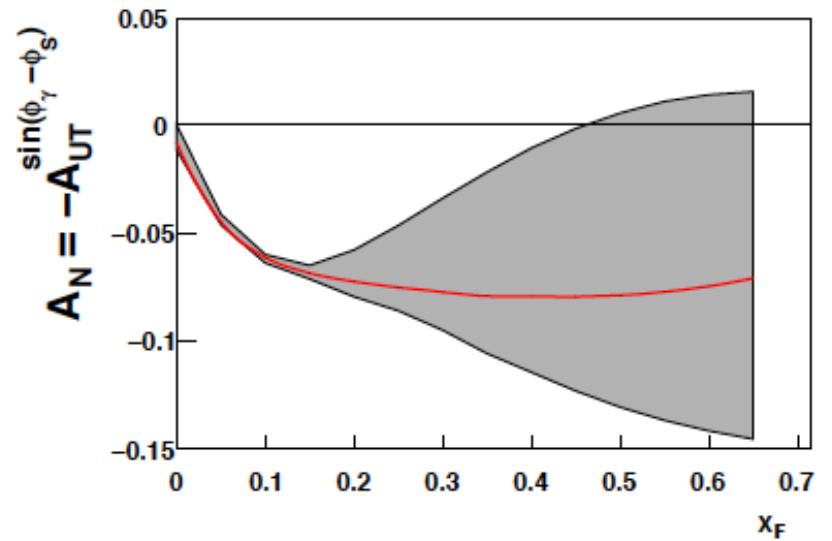


FIG. 5. Prediction for Sivers asymmetry $A_N \equiv -A_{UT}^{\sin(\phi_\gamma - \phi_S)}$ for DY lepton pair production at $\sqrt{s} = 500$ GeV, for the invariant mass $4 < Q < 8$ GeV and transverse momentum $0 < q_\perp < 1$ GeV.

Gamberg, Kang and Prokudin
arXiv:1302.3218

A to-do list and questions on fsPHENIX forward jet simulation

Part-III, forward "jet-like structure" related questions

1. How would one define a "jet-like" structure ? and jet center ?
2. trace each jet-like event to the generator at the parton level, which "sub-process" hard-scattering they come from. quark-quark, quark-gluon, glue-glue etc.
3. Jet rates vs total jet energy, given a standard luminosity.
4. Jet size, Number of particles in a jet, particle species in a jet. ratio of K^+/π^+ , K^-/π^- etc. in a jet. Secondary particles from decays vs prompt particles.
5. Jet shape. Averaged p_t relative to the jet center.
6. Typical fraction of a jet get caught for each detector setup, how much jet energy get lost ?
7. Without any momentum information, how far away is the geometrical jet center (based on charged particles) compare to the real jet center ?
8. With Chris Lee's single-jet-geometrical variable defined as "tau", can we identify quark jet vs gluon jet ?
9. If we catch all he particles in the jet, statistically, would u-quark jet and d-quark jet show up some noticeable difference in the summed-charge ?
10. In the very forward region, how can we separate the hard scattering jet from the "Initial State Radiation jet" ?

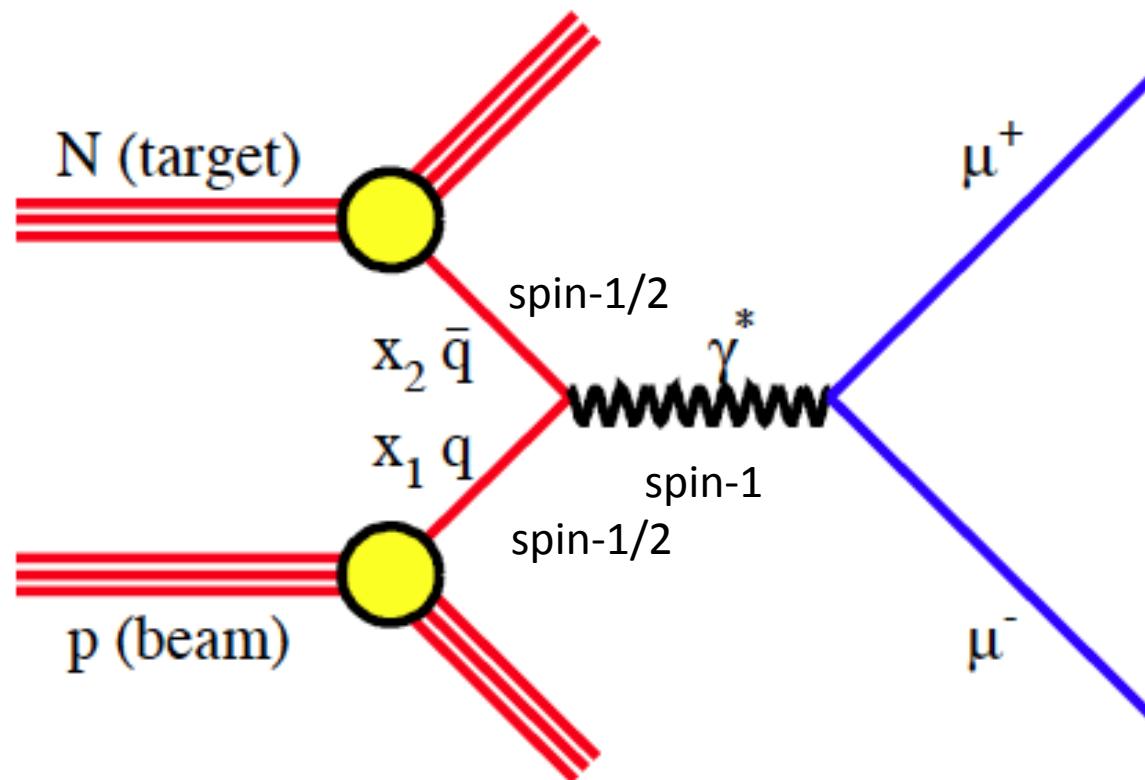
....

More generic questions on fsPHENIX detector design

Part-II. Generic questions for p+p at root_s=200 and 510 GeV, "minimum bias" events.

1. number of particles, $dN/d(\eta)$ distribution, (Compared with BRAHMS forward data)
2. particle flux (rates), with a given standard luminosity, vs momentum at different rapidity regions, for e⁺, e⁻, photon (prompt photon, decayed photon), initial π^0 and η , π^+ , π^- , K⁺, K⁻, p, p_{bar}, etc.
- 3 ... and ratios of π^-/e^- , π^+/e^+ , π^+/π^- , $K^+/\pi^+/p$, $K^-/\pi^-/\bar{p}$, (preparation for particle ID detector design).
4. trace each particle type to the generator at the parton level, which "sub-process" they come from. quark-quark, quark-gluon, glue-glue etc.

Polarized Drell-Yan reaction can provide clean access to sea quarks' polarization, transverse spin (transversity) and angular motion (Sivers distribution).



Drell-Yan in Polarized p+p Collisions

$$A_{LL}^{DY} \propto \Delta q(x_1) \cdot \Delta \bar{q}(x_2)$$

Double-spin asymmetries:

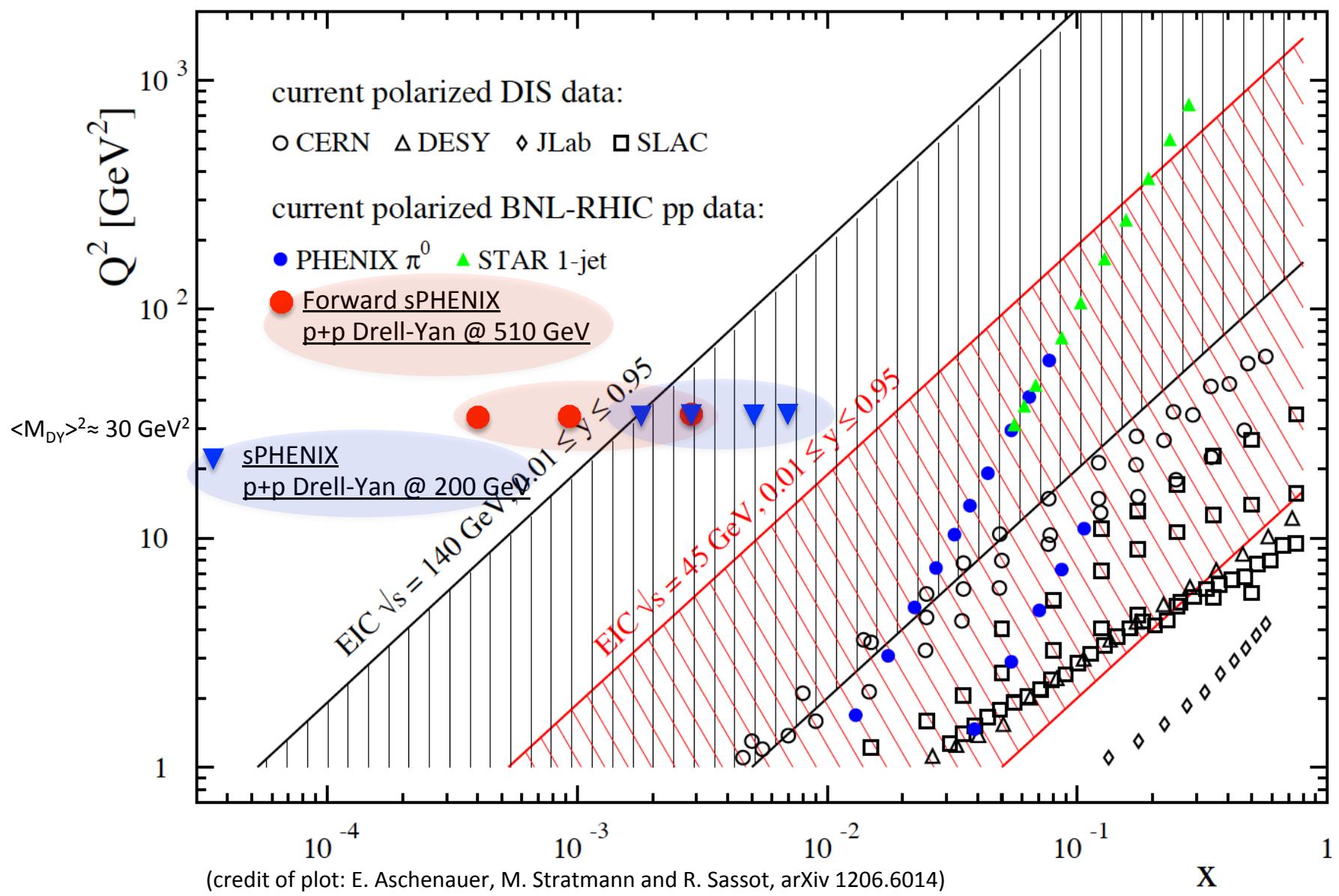
$$A_{TT}^{DY} \propto \delta q(x_1) \cdot \delta \bar{q}(x_2)$$

- A_{LL} clean access to quark and anti-quark helicity distributions.
- A_{TT} clean access to quark and anti-quark transversity distributions.
- A_{LT} clean access to quark and anti-quark “warm-gear” TMDs.

Single-spin asymmetries:

- A_N forward: clean access to valence quark Sivers distributions.
- A_N backward: clean access to anti-quark Sivers distributions.
-
- A_{LU} , ... clean access to quark and anti-quark TMDs.

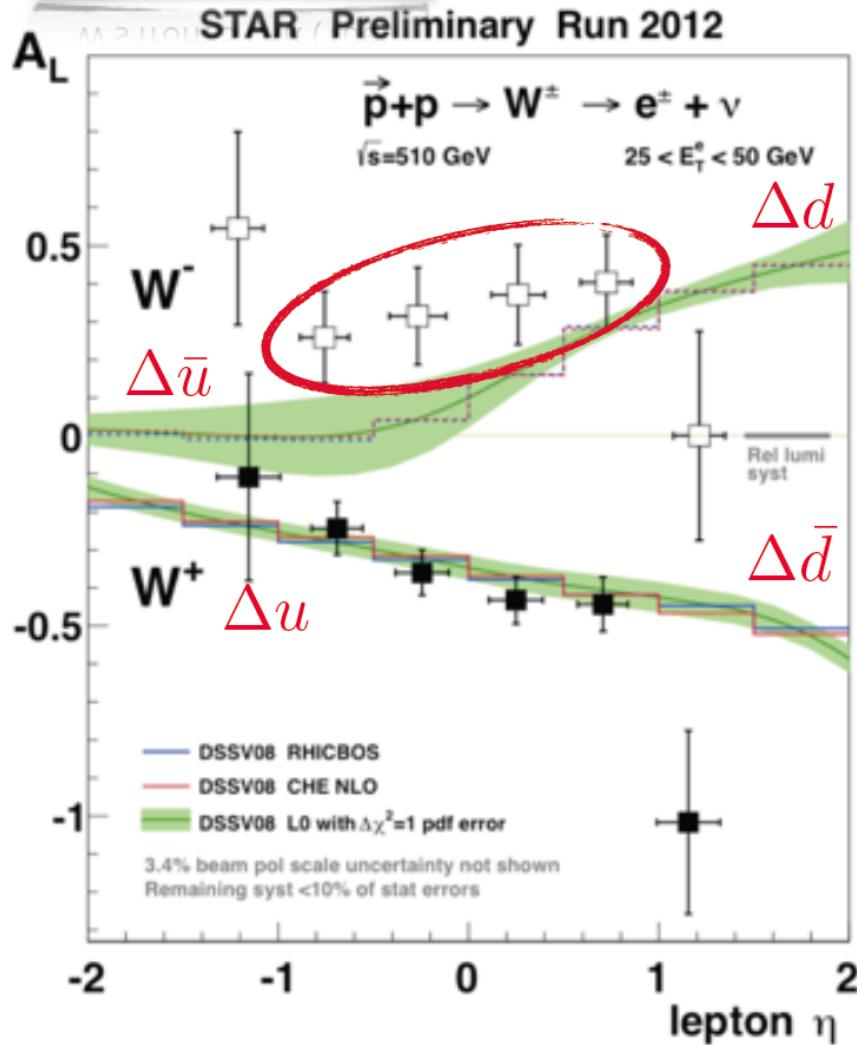
fsPHENIX Drell-Yan x_2 Coverage Compared with Existing Spin Data



deeper into the nucleon sea ...

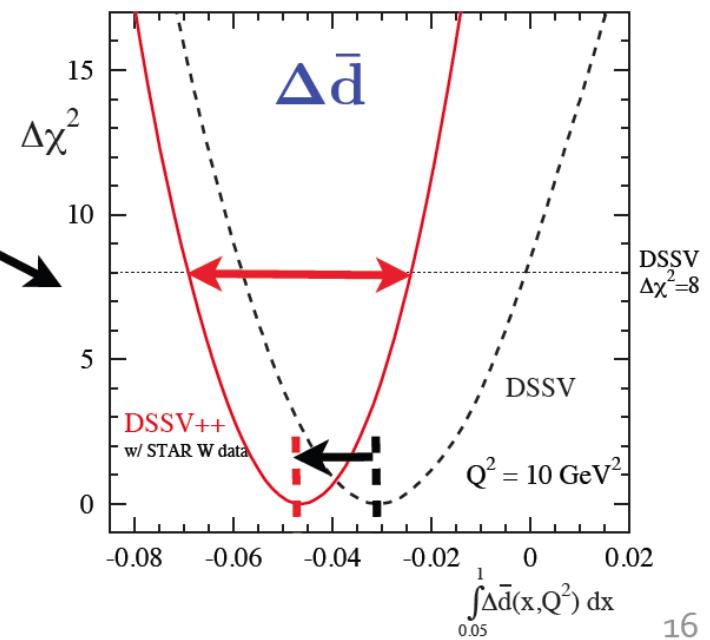
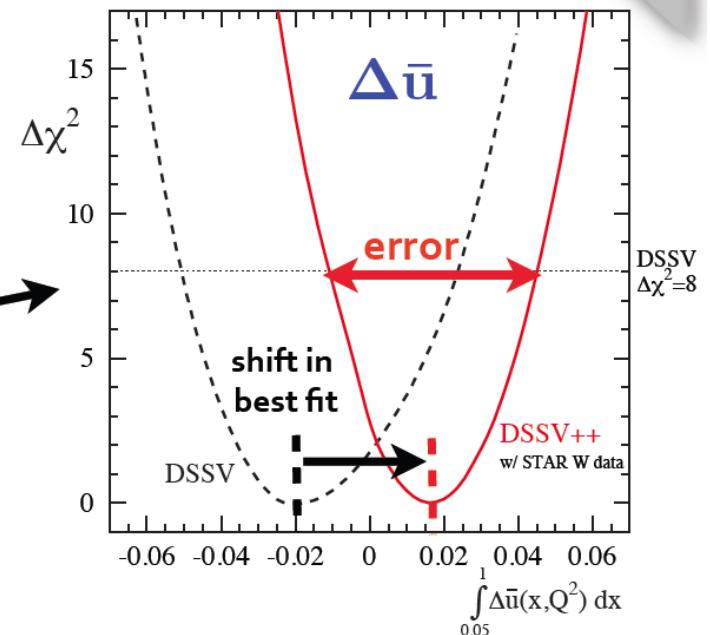
preliminary 2012 STAR data & impact

Surrow
W's from STAR (Tue)



much more to come from current RHIC run
PHENIX muon-arms cover higher eta.

run 12 data
already have
a significant
impact

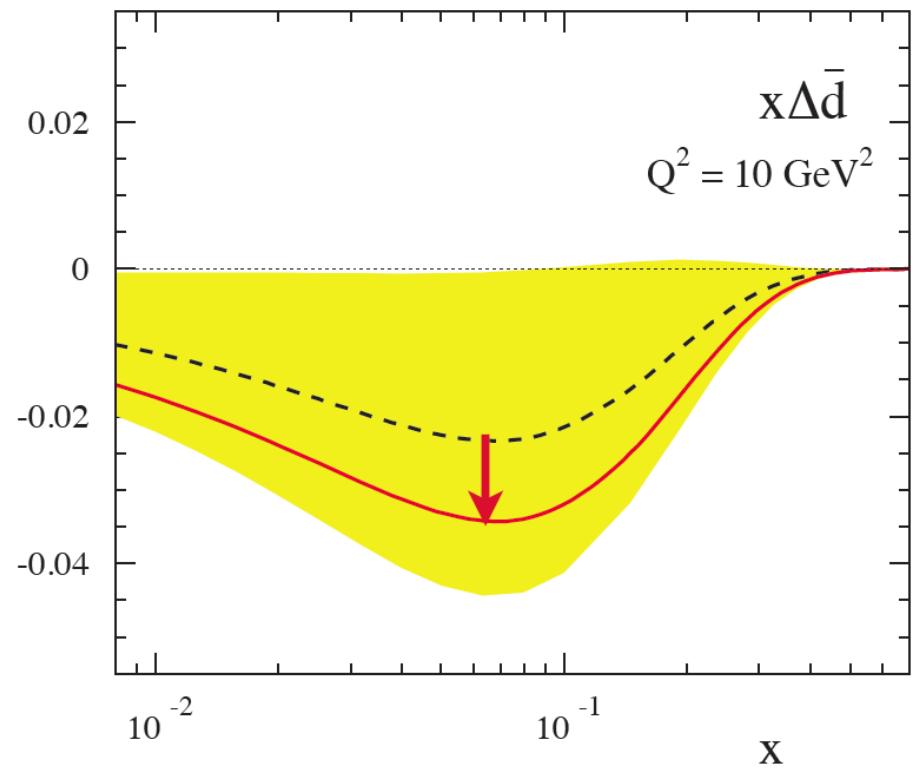
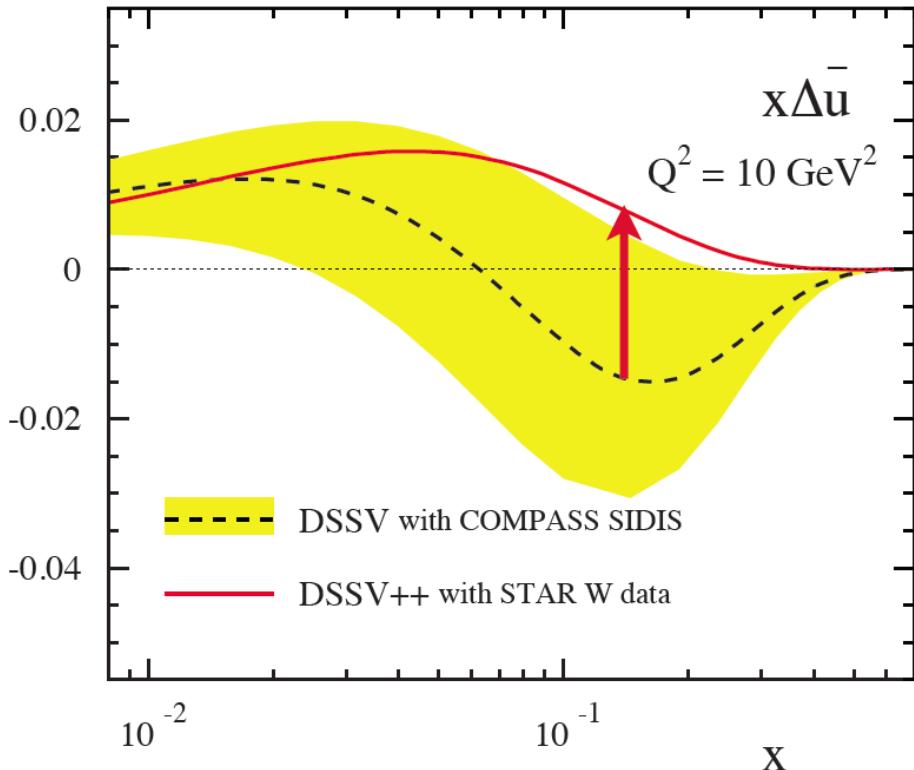


impact in terms of $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$

$\Delta\bar{u}$
 $\Delta\bar{d}$

at $x=0.1$, $x^*\Delta u \approx 0.01 \sim 0.02$

still very preliminary !



- starts to test of what we know about sea quarks from SIDIS with pions
- new fit points towards rather sizable $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ of interest for models

looming (mild ?) tension with SIDIS data

At the leading-order:

$$A_{LL}^{DY} = -\frac{\sum_q e_q^2 \{ \Delta q(x_1) \Delta \bar{q}(x_2) + \Delta \bar{q}(x_1) \Delta q(x_2) \}}{\sum_q e_q^2 \{ q(x_1) \bar{q}(x_2) + \bar{q}(x_1) q(x_2) \}}$$

$$A_{pp} = -\frac{4 \Delta u_1 \Delta \bar{u}_2 + \Delta d_1 \Delta \bar{d}_2 + \dots}{4 u_1 \bar{u}_2 + d_1 \bar{d}_2 + \dots}$$

$$A_{pn} = -\frac{4 \Delta u_1 \Delta \bar{d}_2 + \Delta d_1 \Delta \bar{u}_2 + \dots}{4 u_1 \bar{d}_2 + d_1 \bar{u}_2 + \dots}$$

[Once we have a polarized neutron (${}^3\text{He}$) beam at RHIC.]

$$A_{pp} = - \frac{\frac{\Delta u_1}{u_1} \frac{\Delta \bar{u}_2}{\bar{u}_2} + \frac{1}{4} \frac{d_1}{u_1} \frac{\bar{d}_2}{\bar{u}_2} \cdot \frac{\Delta d_1}{d_1} \frac{\Delta \bar{d}_2}{\bar{d}_2} + \dots}{1 + \frac{1}{4} \frac{d_1}{u_1} \frac{\bar{d}_2}{\bar{u}_2} + \dots}$$

$< \sim 0.15$

$$A_{pn} = - \frac{\frac{\Delta u_1}{u_1} \frac{\Delta \bar{d}_2}{\bar{d}_2} + \frac{1}{4} \frac{d_1}{u_1} \frac{\bar{u}_2}{\bar{d}_2} \cdot \frac{\Delta d_1}{d_1} \frac{\Delta \bar{u}_2}{\bar{u}_2} + \dots}{1 + \frac{1}{4} \frac{d_1}{u_1} \frac{\bar{u}_2}{\bar{d}_2} + \dots}$$

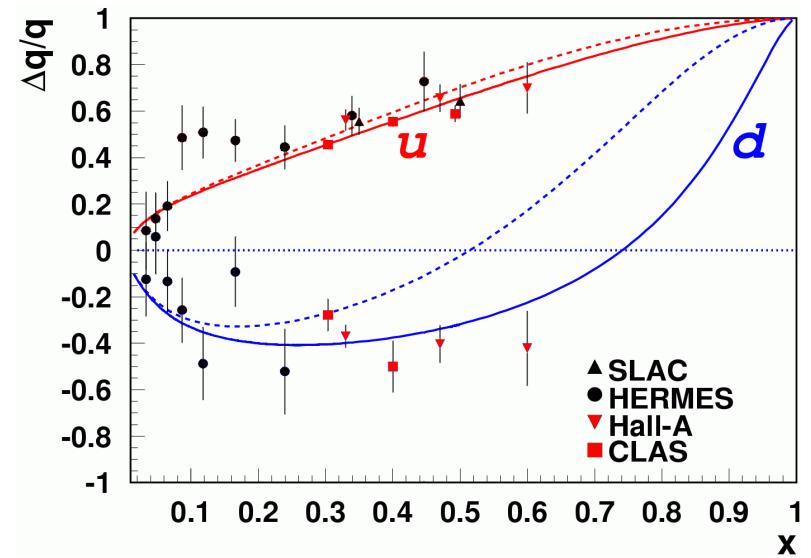
$< \sim 0.07$

to a good approximation:

$$A_{pp} \approx -\frac{\Delta u_1}{u_1} \frac{\Delta \bar{u}_2}{\bar{u}_2}$$

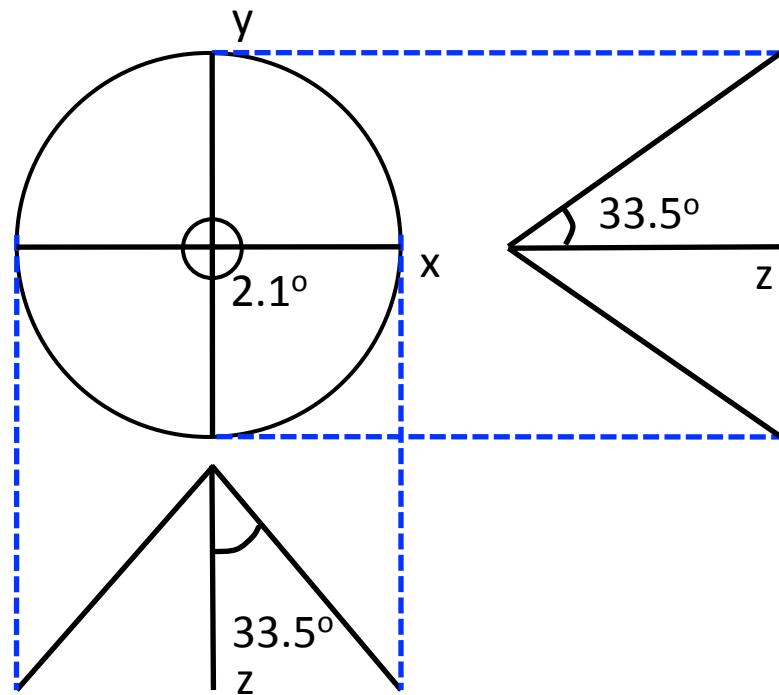
$$A_{pn} \approx -\frac{\Delta u_1}{u_1} \frac{\Delta \bar{d}_2}{\bar{d}_2}$$

The ratio of $\Delta u/u$ is well known from inclusive DIS, will be improved with JLab-12 GeV.



DY Simulations: Geometrical Cuts for fsPHENIX

- Cone shape pseudorapidity, η of $1.2 < |\eta| < 4.0$, which corresponds to $2.1 < \text{degree}, \theta < 33.5$

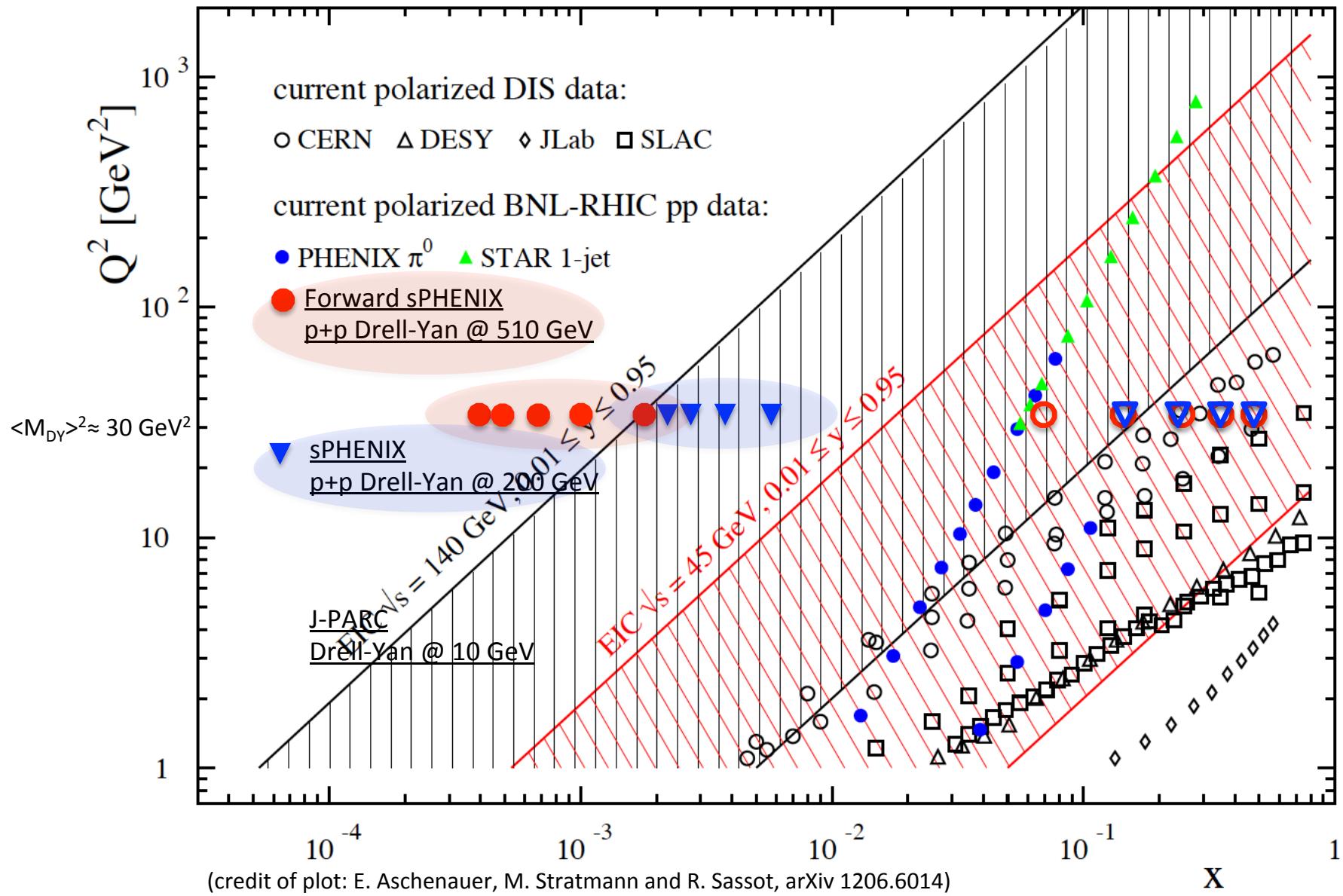


Assume an overall efficiency of $\sim 50\%$.

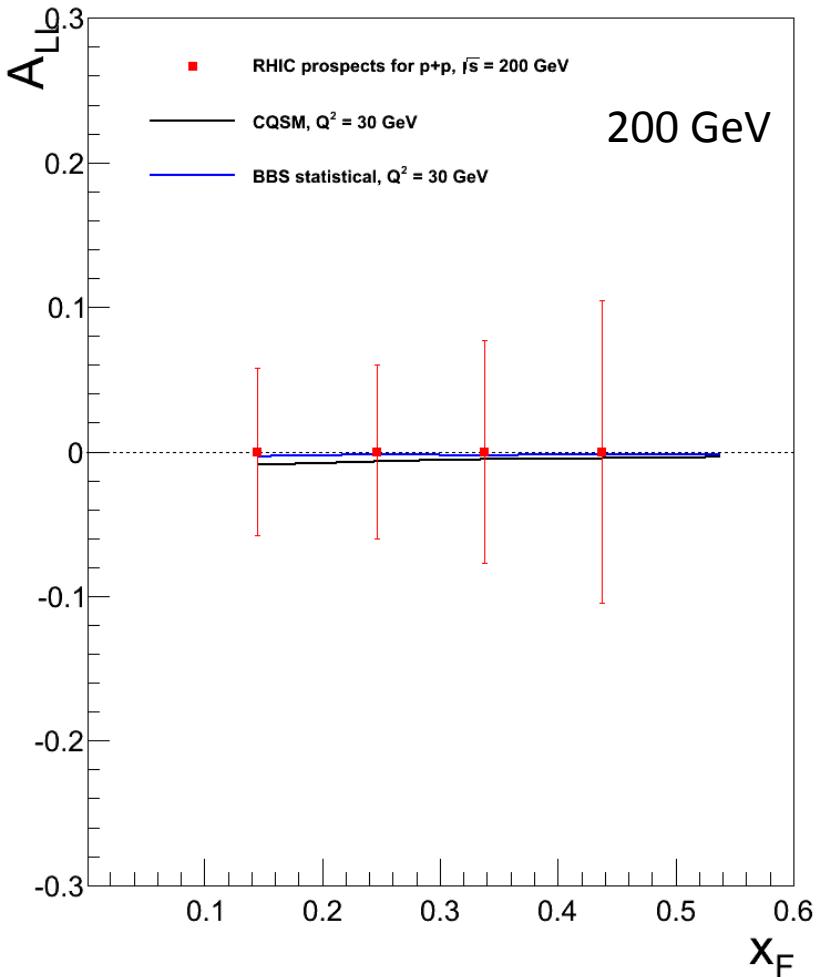
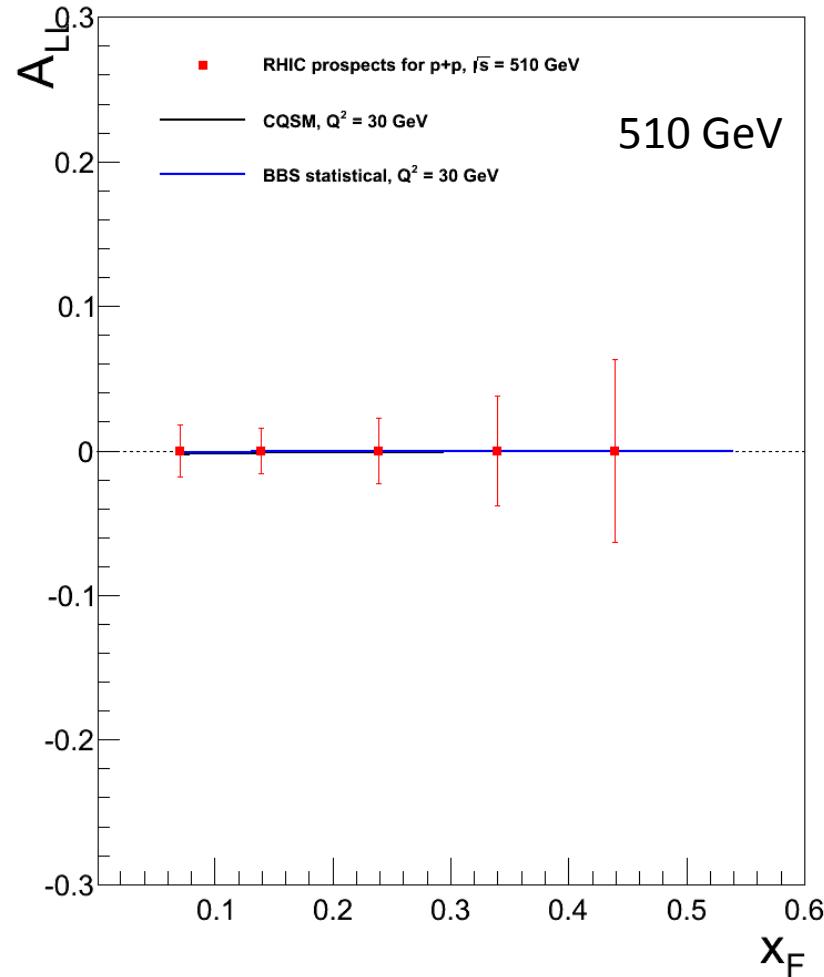
We estimated the DY counts through Pythia simulations (without detector details).

We have not considered issues such as heavy quark decay, backgrounds etc.

Kinematic Access Compared with Existing Spin Data



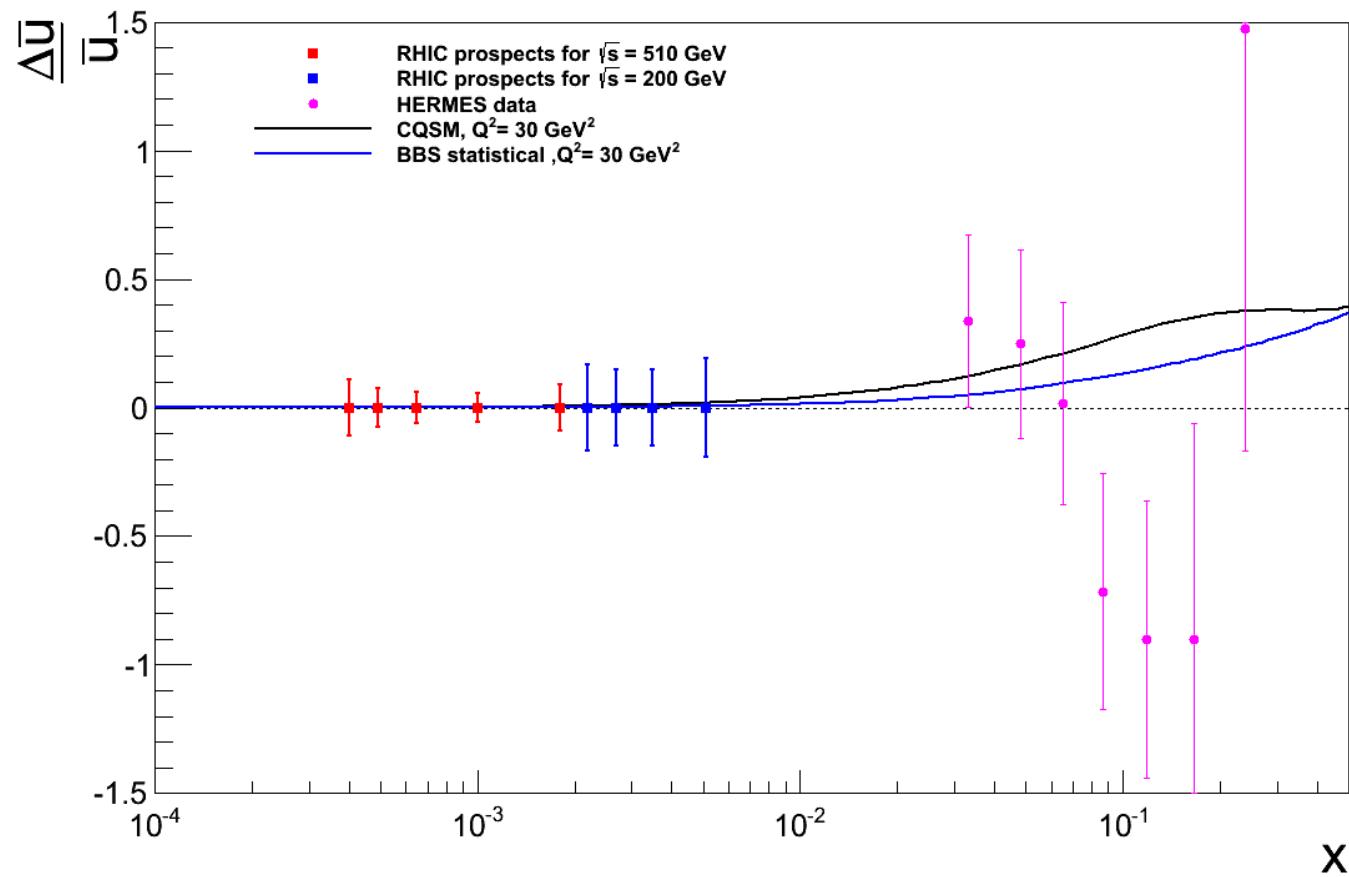
RHIC p+p "prospected data" vs. theory predictions



Theory predictions assumed u-bar carries no polarization.

STAR W- asymmetry data indicates non-zero u-bar polarization, later in this session

RHIC: $\Delta\bar{u}/\bar{u}$ v.s. HERMES SIDIS extracted ratio



A_{TT} to Access Transversity

$$A_{TT}^{DY} = \frac{\sin^2 \theta \cos 2\phi}{1 + \cos^2 \theta} \cdot \frac{\sum_q e_q^2 \{ \delta q(x_1) \delta \bar{q}(x_2) + \delta \bar{q}(x_1) \delta q(x_2) \}}{\sum_q e_q^2 \{ q(x_1) \bar{q}(x_2) + \bar{q}(x_1) q(x_2) \}}$$

where θ is the polar angle of either lepton in the rest frame of the virtual photon, and ϕ is the azimuthal angle between the direction of the polarization and the normal to the plane of the di-lepton decay.

$\langle \cos(2\phi) \rangle \approx 2/\pi$, i.e. almost cover all DY azimuthal angles.

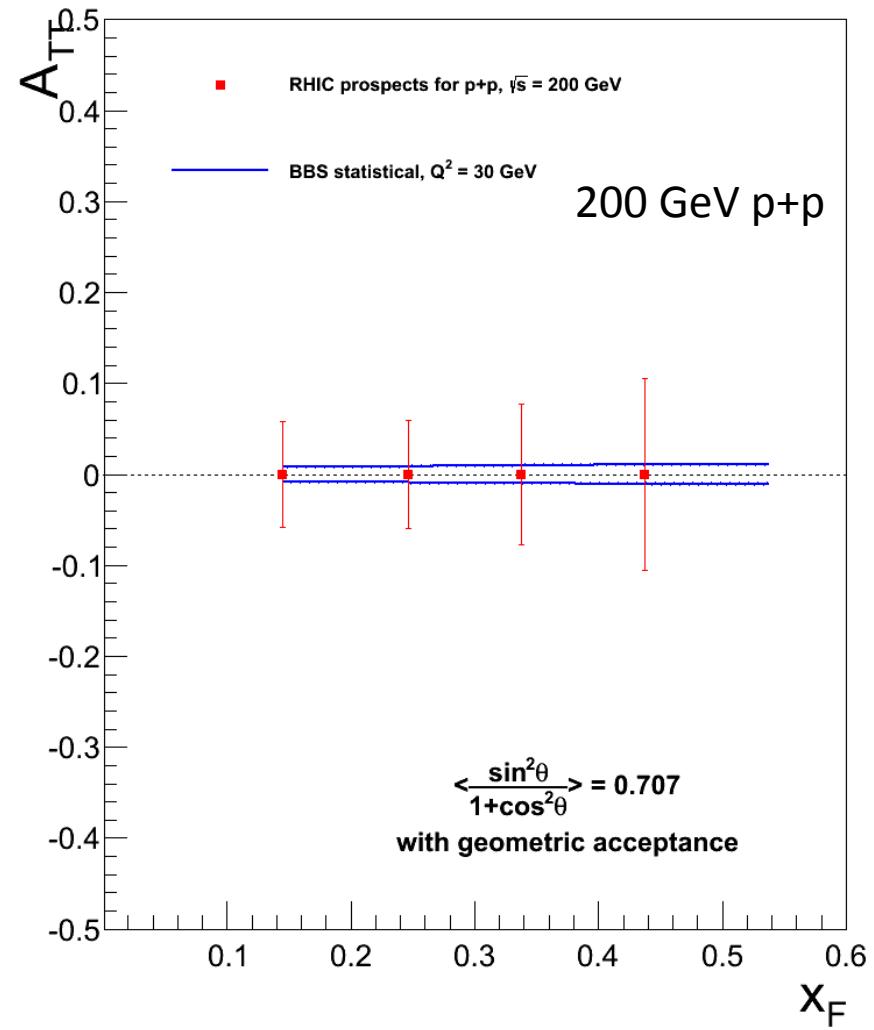
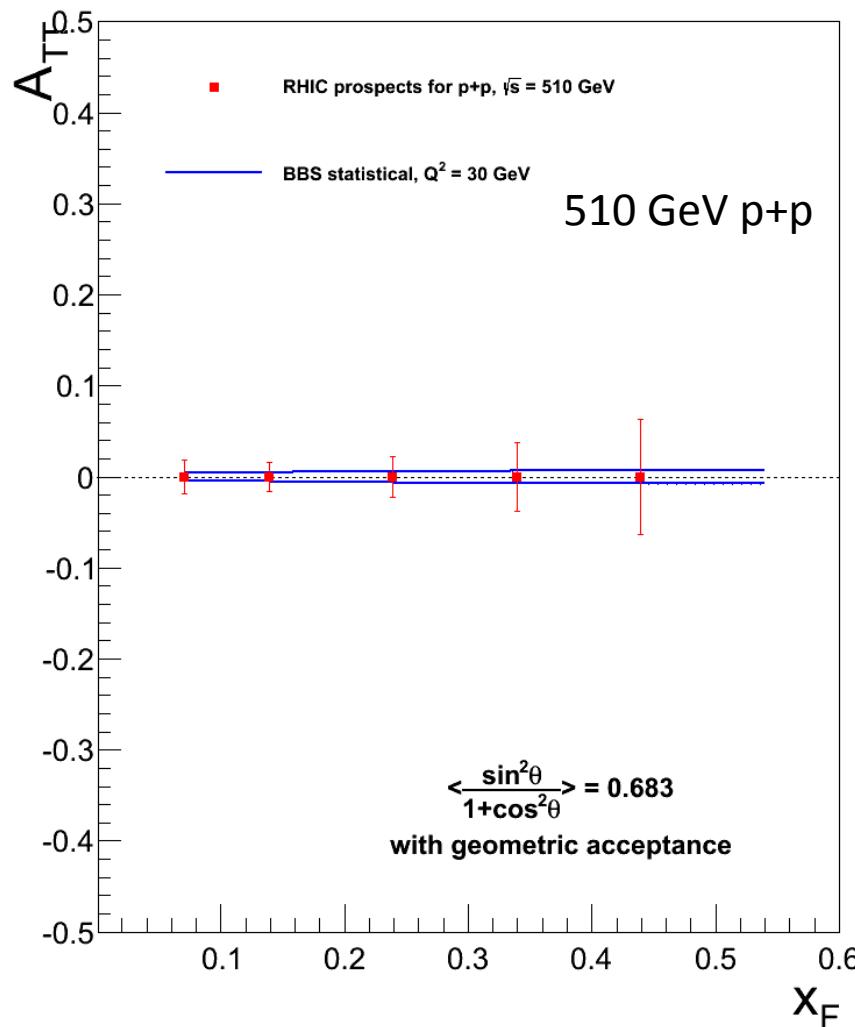
$$\left\langle \frac{\sin^2 \theta}{1 + \cos^2 \theta} \right\rangle = 0.414 \quad \text{if cover all } \theta, \text{ peak at 1.0 for } \theta=90^\circ.$$

Lacking knowledge on transversity, we took the Soffer (positivity) bounds for both quark and anti-quark, i.e:

$$\delta q(x) \leq \frac{1}{2} |q(x) + \Delta q(x)| \quad \delta \bar{q}(x) \leq \frac{1}{2} |\bar{q}(x) + \Delta \bar{q}(x)|$$

We can also try Anselmino group's fits results of quark transversity, later.

RHIC "prospected data" vs. theory predictions.



Theory predictions take $u\bar{u}$ transversity ≈ 0

Existing Fits: Quark Transversity:

fit of semi-inclusive DIS data

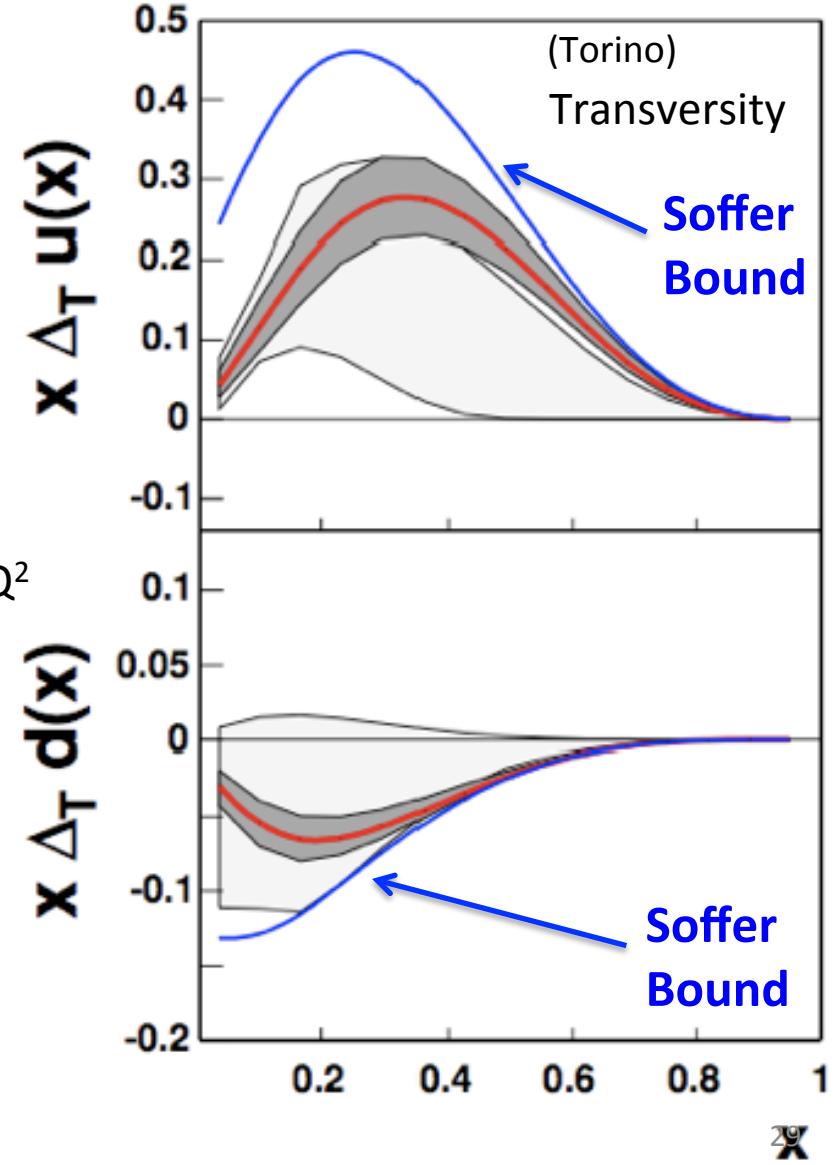
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Soffer Bounds:

$$\delta q(x) \leq \frac{1}{2} |q(x) + \Delta q(x)| \quad \delta \bar{q}(x) \leq \frac{1}{2} |\bar{q}(x) + \Delta \bar{q}(x)|$$

A tighter bound: use the Soffer bounds at a low- Q^2 scale, evolve to higher Q^2 .

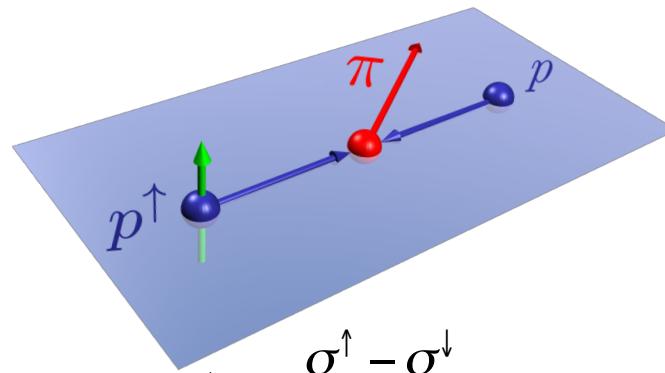
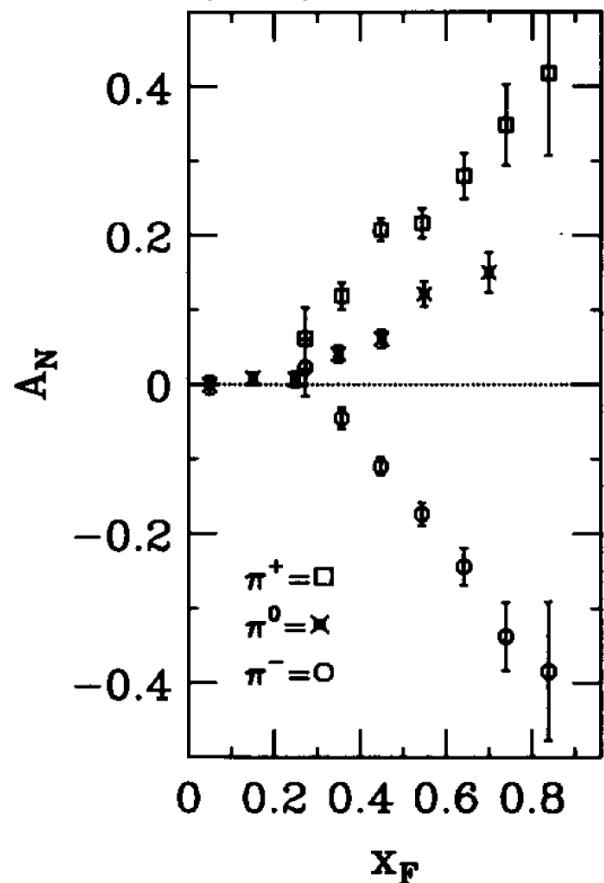
From Collins asymmetry of semi-inclusive DIS (HERMES proton, COMPASS deuteron), and BELLE's correlation asymmetry in $e^+e^- \rightarrow \pi^+\pi^-$



Single-Spin Asymmetry in $p p^\uparrow \rightarrow \pi X$

E704 vs =20 GeV.

PLB 264 (1991) 462.

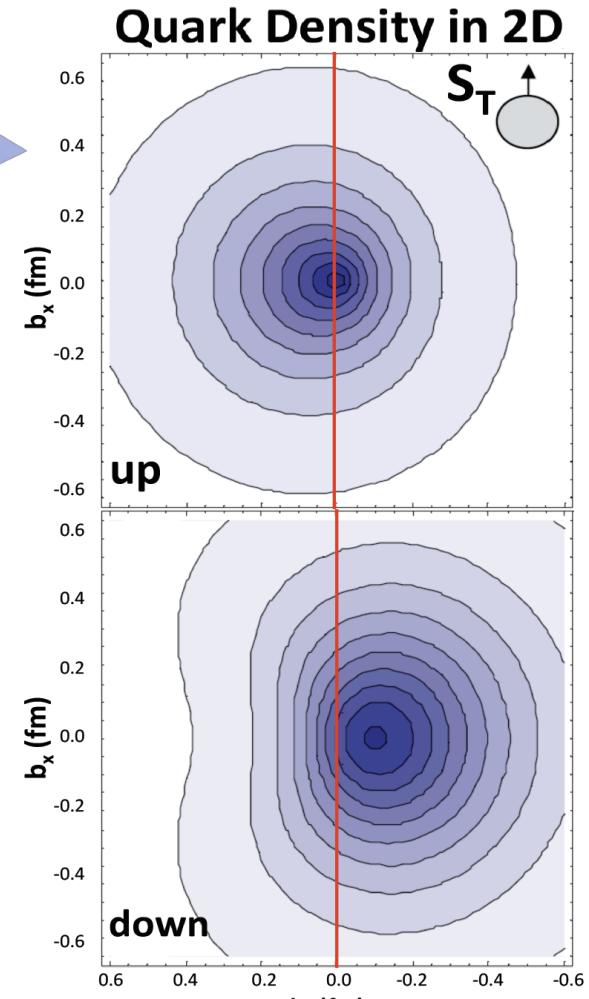


$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$

π^+ ($u\bar{d}$) favors left

π^- ($d\bar{u}$) favors right

One possible explanation (Sivers effect): quark transvers motion generates a left-right bias.

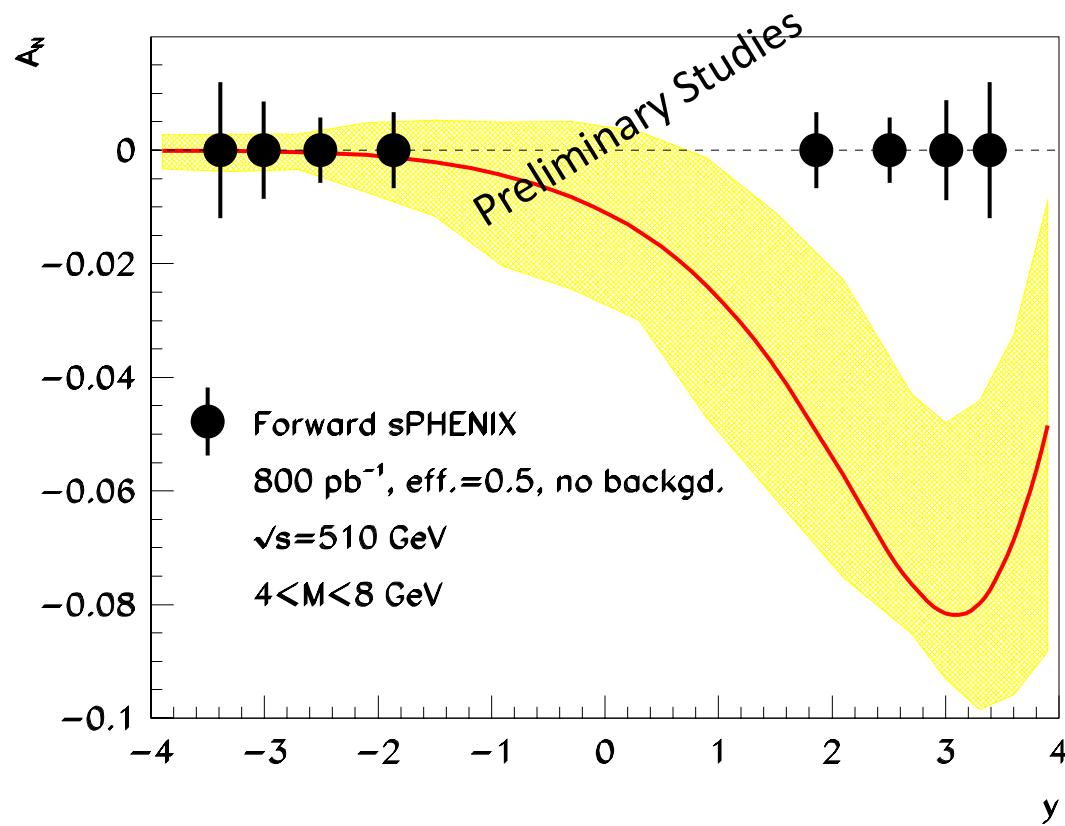


Lattice QCD PRL98:222001, 2007.

Fig. 4. A_N versus x_F for π^+ , π^- and π^0 data.

Quarks in a transversely polarized nucleon can tell left-right,
up-quarks favor left, down-quarks favor right.

Drell-Yan Single-Spin Asymmetry



fsPHENIX physics: my wishlist

- Polarized Drell-Yan
 - single-spin asymmetry: quark Sivers. quark TMDs.
 - double-spin asymmetries: sea quark polarization. Transversity.
- Forward jets A_N : quark Sivers.
- Hadron azimuthal distributions inside a jet: quark transversity.
- Prompt photon A_N : quark Sivers.
- Forward Lambda polarization: transversity coupled with spin-dependent fragmentation.
- Forward Lambda polarization inside a jet: quark transversity.

Drell-Yan SSA to Access Quark TMDs

 : Nucleon Spin  : Quark Spin

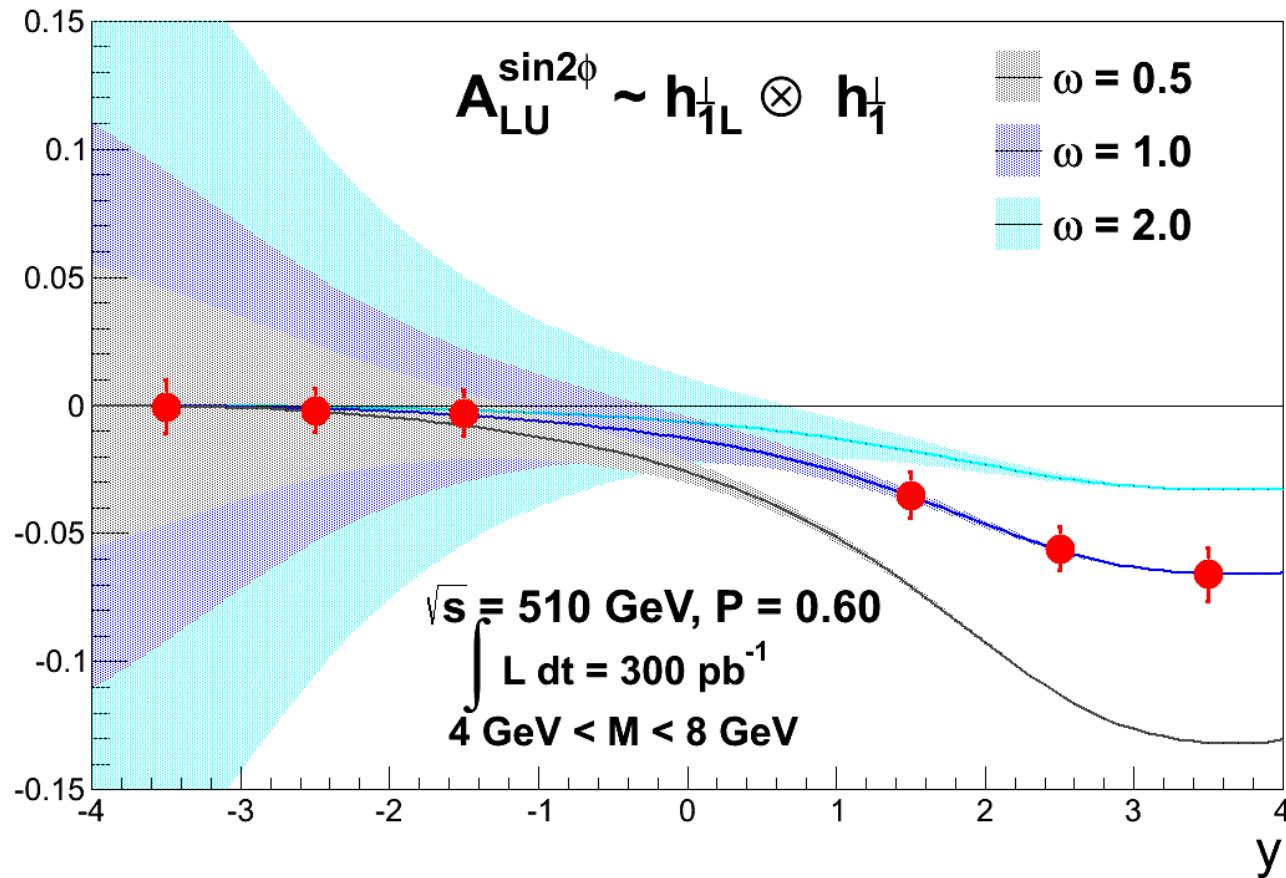
		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \bullet$		$h_1^\perp = \bullet - \bullet$ Boer-Mulders
	L		$g_{1L} = \bullet - \bullet$ Helicity	$h_{1L}^\perp = \bullet - \bullet$ Worm Gear
	T	$f_{1T}^\perp = \bullet - \bullet$ Sivers	$g_{1T} = \bullet - \bullet$ Worm Gear	$h_1 = \bullet - \bullet$ Transversity $h_{1T}^\perp = \bullet - \bullet$ Pretzelosity

For example: $A_{LU}^{\sin 2\phi} \propto \sum_q h_{1L}^{\perp,q} \otimes h_1^{\perp,\bar{q}}$

$h_{1L}^{\perp,q}$ quark's "Longitudinal Transversity", describe quark's transverse polarization inside a longitudinally polarized nucleon.

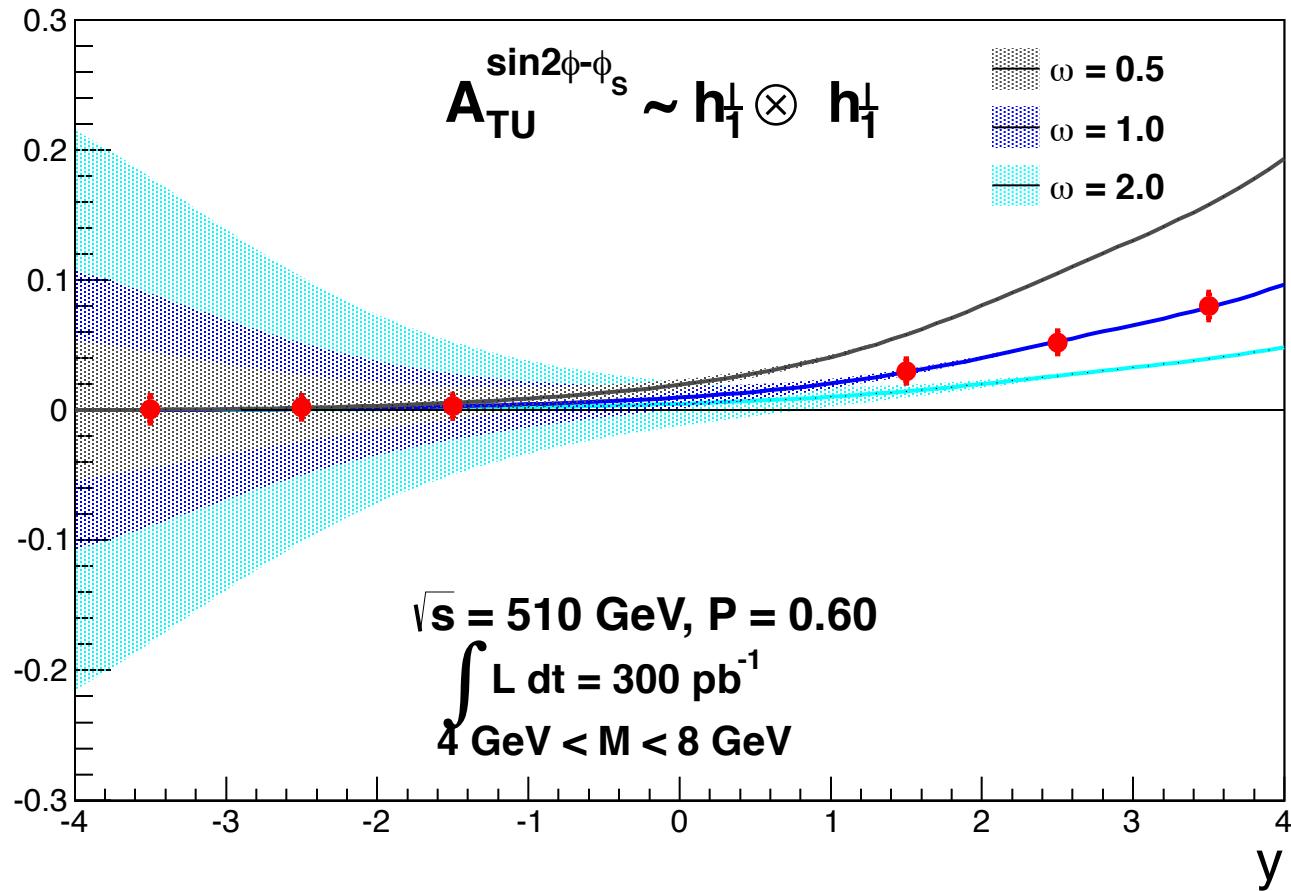
If quarks carry zero angular momentum $\rightarrow A_{LU}^{\sin 2\phi} \equiv 0 !!!$

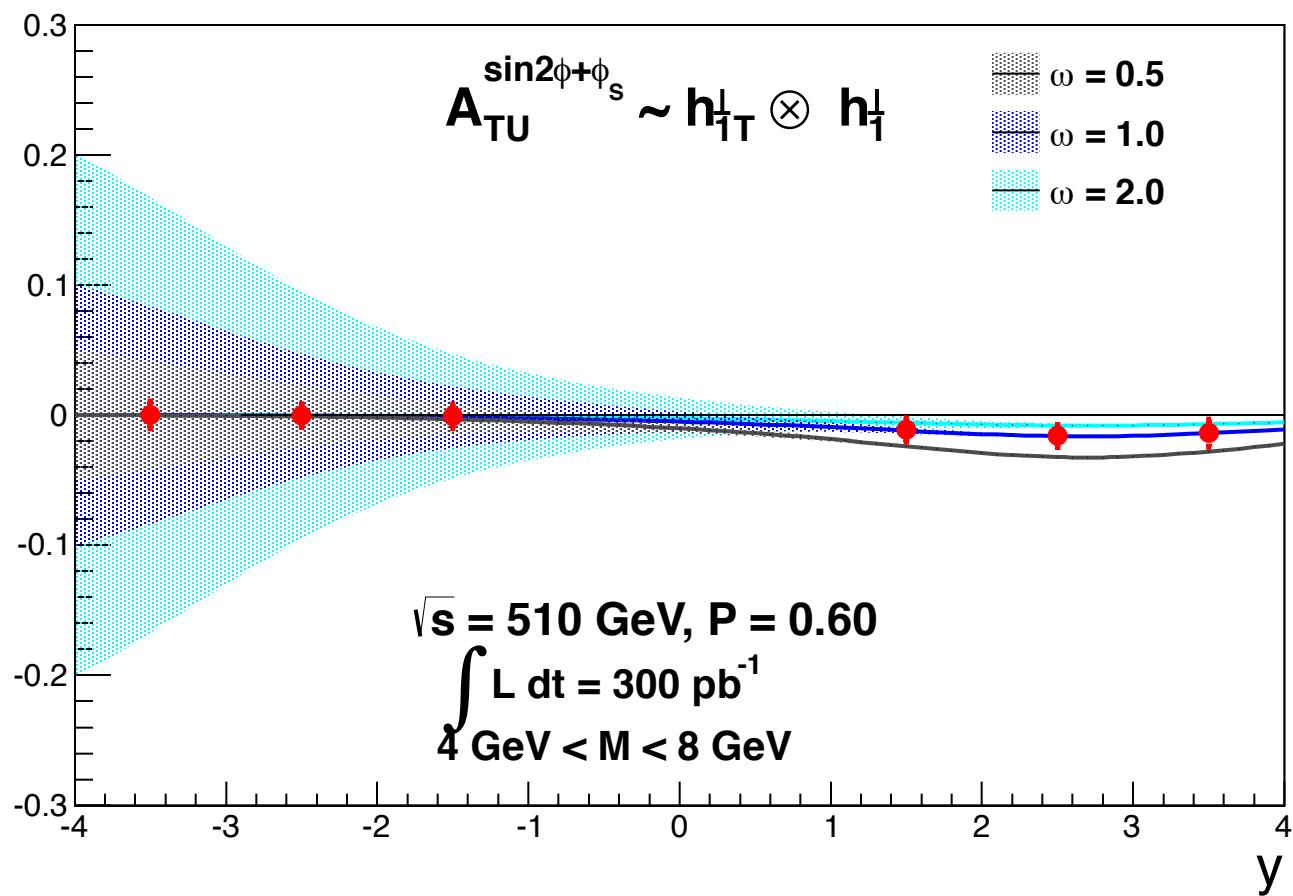
$A_{LU} (L = 300 \text{ pb}^{-1})$



If quarks carry zero angular momentum $\rightarrow A_{LU}^{\sin 2\phi} \equiv 0 !!!$

Access to Transversity



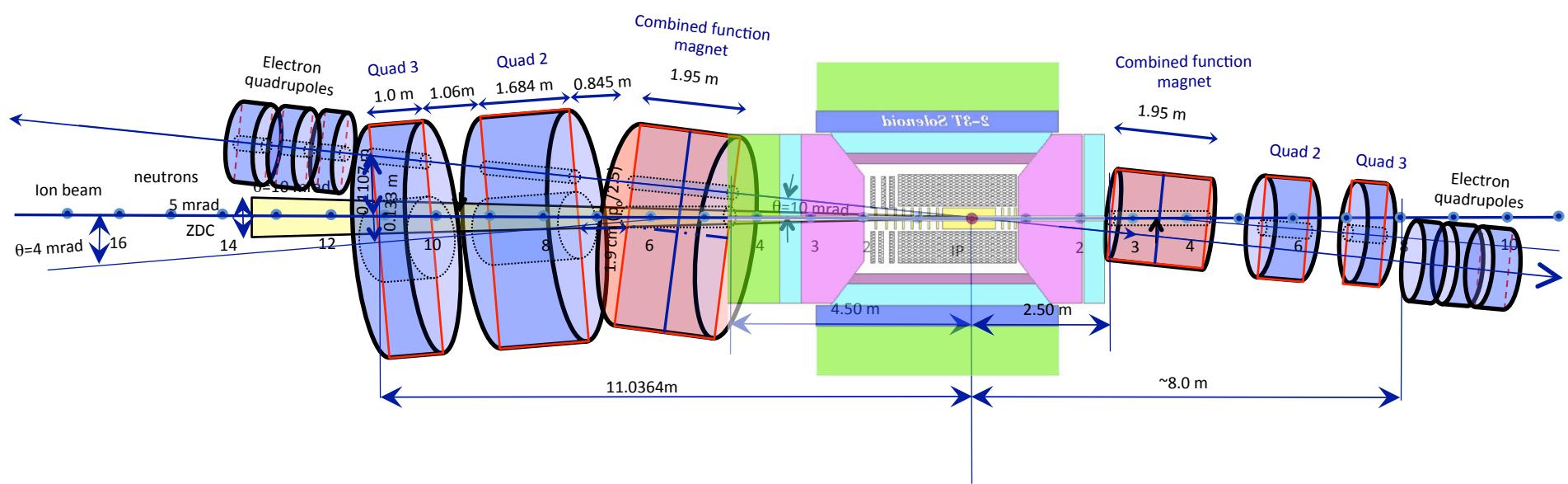


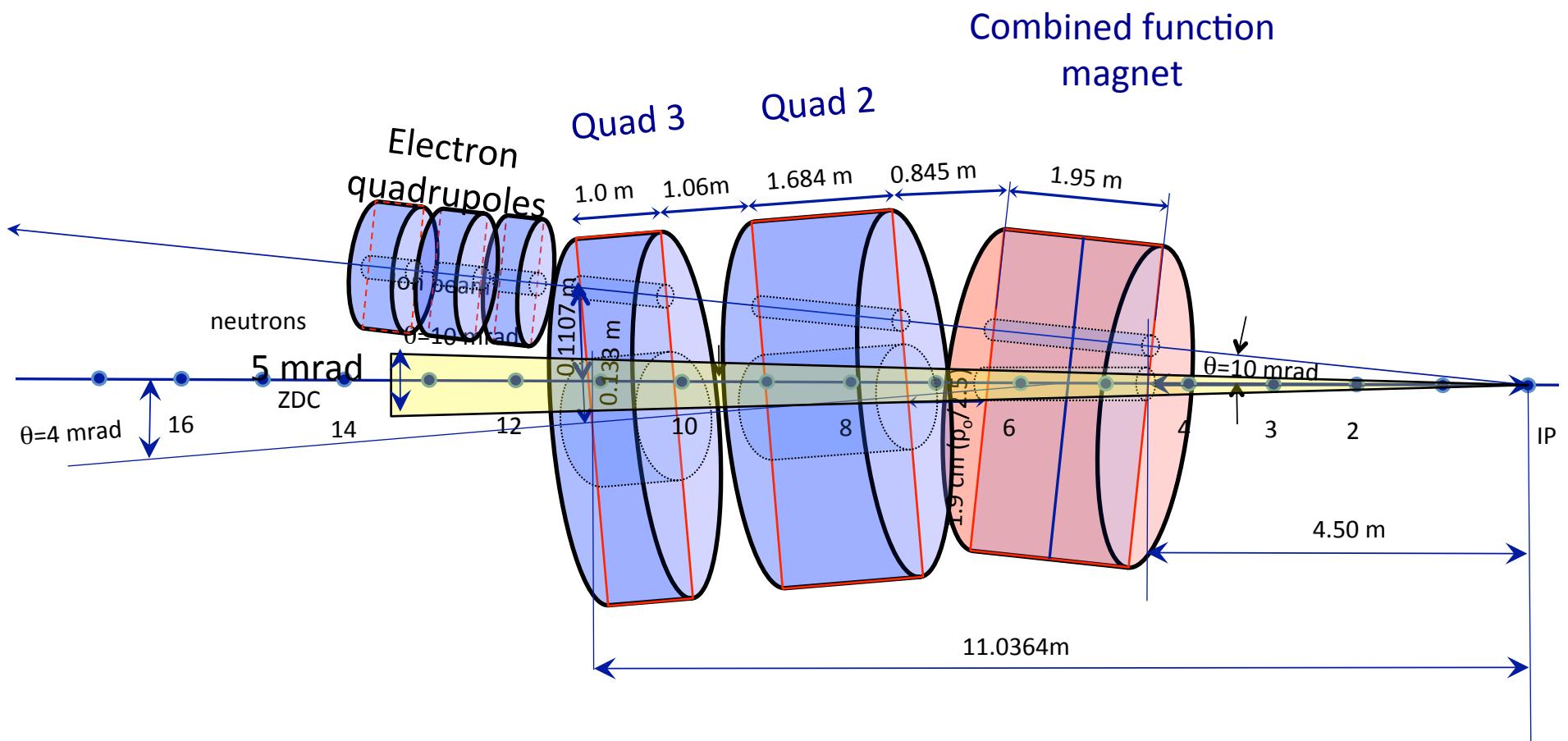
	$\langle x_1 \rangle$ bins	$\langle x_2 \rangle$ bins	$\langle \text{rapidity} \rangle$	σ_{pp}	Number of Events	$\delta(A_{\text{raw}})$	$\delta(A_N)$
RHIC $p \uparrow + p \uparrow$ 510 GeV (AN only 300 pb $^{-1}$)	0.072 0.14 0.24 0.38	0.0018 0.0010 0.00065 0.00046	1.86 2.51 3.01 3.39	228 pb 314 pb 133 pb 73 pb	45.6k 62.8k 26.6k 14.6k	6.6×10^{-3} 5.6×10^{-3} 8.7×10^{-3} 1.2×10^{-2}	1.10×10^{-2} 9.4×10^{-3} 1.44×10^{-2} 1.95×10^{-2}

Note:

- To get $\delta(A_{\text{raw}})$, consider 50% detector efficiency.
- beam polarization: 0.6
- cross sections are calculated after considering fsPHENIX detector geometry acceptance.

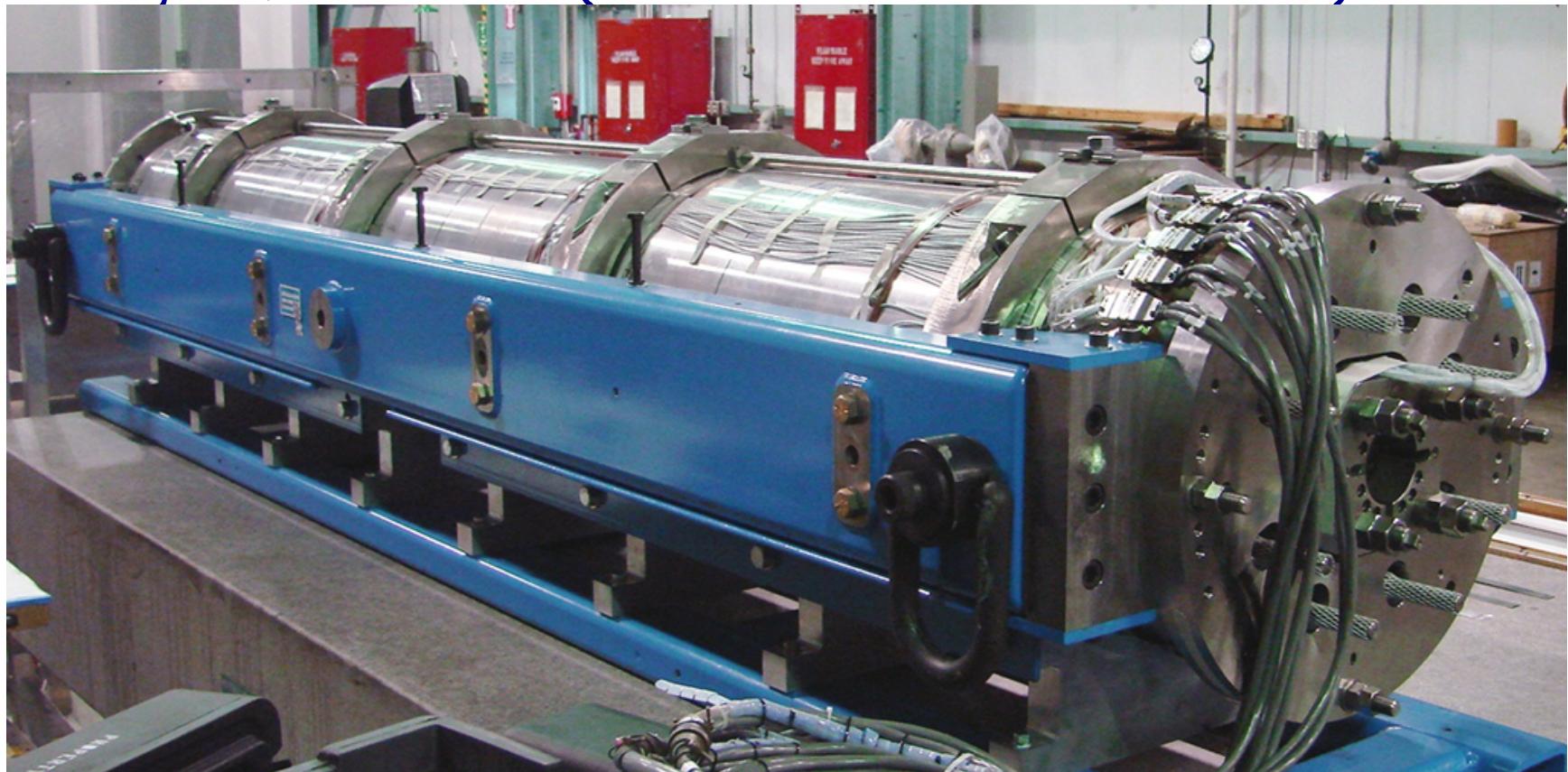
Magnet and Detector Layout



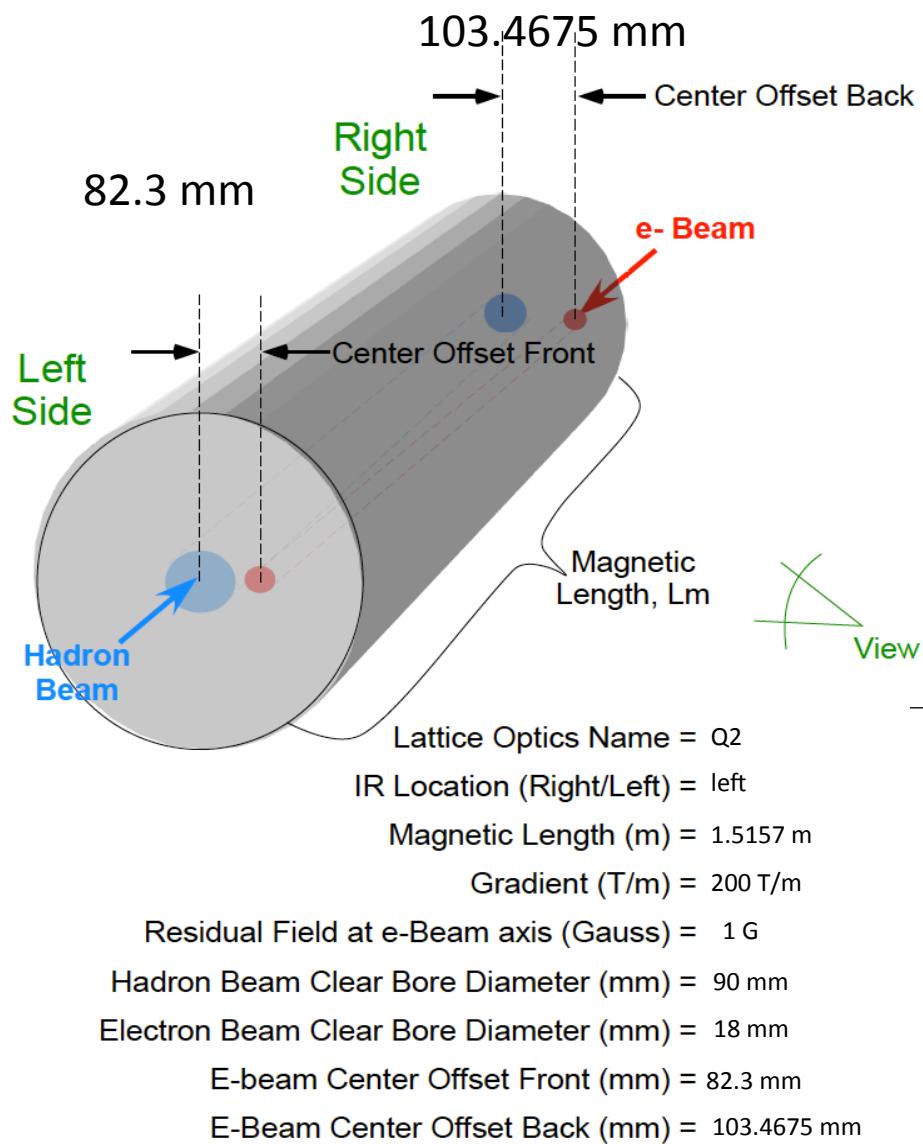


Present technology of the superconducting magnets

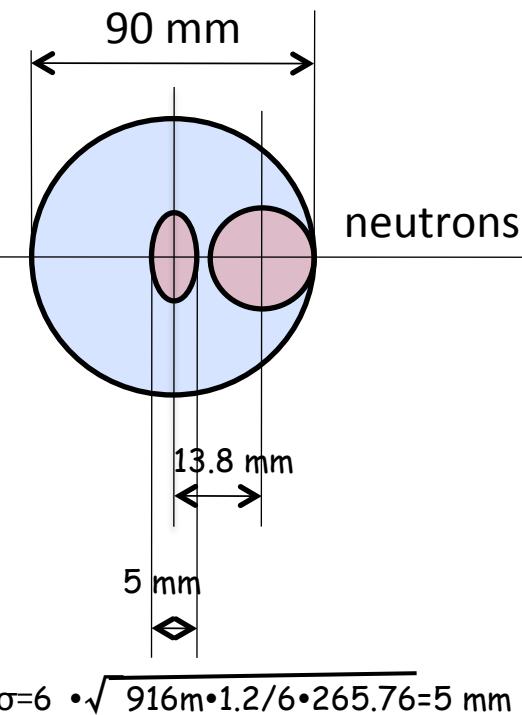
- LARP triplet magnet designed, build and tested with $A=90$ mm and $G=200\text{T/m}$
- Special combined function magnets with no magnetic field region for electron (Brett Parker-BNL-March2011)



Q2



Hadron Aperture Q₂



Name & Date filled Out _____